UDC 551.509.54:551.506.7:551.507.362.2(415)

Forecasting Daily Rainfall From Satellite Data

ERIC C. BARRETT—*Department of Geography, University of Bristol, Bristol, Great Britain*

ABSTRACT—This paper outlines a rainfall forecasting model involving satellite nephanalyses and certain conventional weather data for application in regions where the rain-bearing clouds are advectional rather than convectional. Essentially, the scheme depends upon the selection each day of an appropriate cloud quadrant for the station in question and the evaluation of a "rainfall prediction index" for that quadrant, embracing its synoptic weather organization, its mean cloud cover, and its included cloud types. The rainfall prediction index is then used to forecast a class of rainfall for the day ahead in terms of "no rain," "light rain," "moderate rain," or "heavy rain;" being interpreted through tabulations of related rainfall measurements.

The essential indices are specified for Valentia, Republic of Ireland, from January through June 1967. Rainfall "forecasts" are then made for July through December 1967 using these indices, and the results are discussed. Verification of these forecasts indicates a ratio of approximately 3:1 when they are classified on a simple right:wrong basis. Probable sources of error are indicated and discussed. Several approaches for extending and improving the model are suggested. It is concluded that the method could be profitably applied in weather and hydrological forecasting programs for regions that receive their rainfall from clouds advected from oceanic areas poorly documented by conventional weather observations.

1. INTRODUCTION

Since the first fully operational weather satellite system was inaugurated by the launching of ESSA 1 and 2 in February 1966, much attention has been paid to the interpretation of weather satellite data in terms of conventionally observed atmospheric parameters. Various aspects of cloud fields and many components of the energy budget are examples of such parameters. Precipitation totals and intensities, however, have received scant attention, despite the stated aim of the World Meteorological Organization to evaluate rainfall intensities every 12 hr at least by the categories "Heavy," "Moderate," and "Light" by the end of 1971. (WMO 1967).

Currently, there seems to be a rising demand for a simple operational rainfall forecasting model capable of yielding satisfactory results on a daily basis. This demand stems partly from the growing number of national weather centers operating automatic picture transmission (APT) receiving stations, and partly from a growing realization of the potential usefulness of such information in hydrology, especially in catchment basin studies and flood forecasting.

In a Committee on Space Research Status Report on the application of space technology to the World Weather Watch, the following three possible types of approach to the problem of rainfall estimation were suggested (COSPAR 1967):

1. "Passive" methods by which precipitating clouds would be distinguished from nonprecipitating clouds through differences in radiation emitted from the raindrop clouds and their backgrounds. This could possibly be achieved by scanning simultaneously through wavelengths longer than 1 cm (where thin, nonprecipitating clouds are fairly transparent) and either visible or atmospheric window wavebands [through which total cloud cover can be assessed (Thaddeus 1966)].

2. "Active" methods in which precipitating clouds are distinguished from their surroundings and backgrounds through differences in reflection characteristics. One specific possibility was investigated by Dennis (1963), who considered the possibility of detecting rain with satellite-based radar.

3. "Delayed response" methods in which surfaces recently exposed to precipitation are identified by infrared analyses. For example, rain falling on a cold ocean leaves a warm, nonsalty layer on the surface, and this relatively stable layer may persist in an identifiable form for some time. Over land, rain-soaked terrain may be identified by its decreased emissivity in window wavebands or decreased reflectivity in the visible portion of the electromagnetic spectrum. The latter relationship was used to detect areas of precipitation from Gemini space photographs. (Hope 1966).

In practice, however, the most widely used group of methods has been a fourth type, statistical in nature. Such methods depend on appropriate comparisons of satellite and conventional data. Some have utilized infrared measurements (e.g., Lethbridge 1967, Clapp and Posey 1970), and others have used photographic data (e.g., Johnson et al. 1969). The present writer utilized standard U.S. National Weather Service nephanalyses in the construction of monthly maps of estimated rainfall over substantial areas of the tropical Far East (Barrett 1970, 1971). Those maps were compiled following considerations of percentage cloudiness, the probabilities of falls of rain from different categories of clouds, and the likely intensities of those rainfalls at the intersections in a chosen geographic grid. Synoptically significant cloud masses were accorded heavier rainfall intensities than the rest of the regional cloudiness. Monthly cloud characteristics were translated into rainfall estimates via a regression line that related a trial set of "rainfall coefficients" to appropriate rainfall observations. The method gives acceptable results over periods of 1 mo, the time unit for which it was designed. (See Barrett 1971, figs. 5, 6.)

More recently, this method has been adapted by

Follansbee (1972, 1973) for application to the more difficult problem of daily rainfall estimation. Daily rainfall totals are harder to estimate accurately since the rainfall performance of seemingly similar cloud fields can be different from one day to the next. Such differences tend to be averaged out over longer periods such as 1 mo. Follansbee replaced the original "stratiform" category with "nimbostratus" and "cumuliform" with "cumulus congestus." These, along with cumulonimbus, were the only cloud types believed to yield enough rainfall to be significant. The stratiform coefficient of 0.25 was retained for nimbostratus, and the cumuliform coefficient of 0.02 for cumulus congestus. The cumulonimbus coefficient of 0.72, however, was increased from 0.72 to 1.00. Other important differences in Follansbee's approach were his use of satellite photographs rather than nephanalyses as the basic data, and his concern with mean daily rainfall across selected areas rather than with individual totals for selected point locations. Applications of this modified method to regions as far apart as California, Florida, Zambia, and Thailand seemed to provide worthwhile results.

Meanwhile, so far as rainfall *forecasting* is concerned, little progress has so far been made, although it has become obvious from the *estimation* techniques that any viable method should lend itself to tailoring to the special conditions in each forecast area. The research program outlined in the present paper involved the construction and initial testing of such a model. Although it involves certain principles and procedures similar to those outlined above, its basic purpose is dissimilar, concerned as it is with future rather than past or present rainfall.

In addition, the new model relates to rainfall at a single station instead of mean daily rainfall over selected areas, although it would not be difficult to introduce variations permitting it to be applied to regional rainfall forecasting also.

2. THE DESIGN OF A DAILY RAINFALL FORECASTING MODEL

Background Considerations

It was decided initially to base the model upon cloud field characteristics at the commencement of the forecasting period, identifying those areas of cloud most likely to affect the station in question during the next 24 hr, and interpreting these in terms of anticipated rainfall totals. Such a method seemed to be most sure of success in regions where rainfall is mainly associated with advectional rather than convectional processes. Where cloud development and dissipation is often rapid and short term, as it is within much of the humid Tropics for example, such a method might not be as appropriate as in the depression belts of middle latitudes. Consequently, attention was focused on the principal meteorological station of Valentia in the Irish Republic (51°65′N, 10°15′W, altitude 9m) as a convenient representative of a predominantly advectional weather regime. This station was chosen to illustrate the tailoring of the basic model to local conditions, and to test the acceptability of its results. Valentia seemed a good choice since:

1. It is open to the Atlantic weather systems that pass over southern Ireland and largely determine the precipitation climatology of the region.
2. Its weather is little-influenced by abrupt relief or topography.
3. Radiosonde flights are made from Valentia twice daily at approximately midday and midnight in addition to the conventional surface weather observations.
4. Both surface and upper air data for Valentia are reported in daily publications of the British Meteorological Office; namely, the Daily Weather Report and the Daily Aerological Record, respectively. The author had easy access to these publications.

Theoretically it seemed that, under a predominantly advectional type of weather regime, daily rainfall, RR, could be conceived as a function of three variables in particular:

1. The dominant organization of the synoptic weather, S.
2. The proportion of sky which is cloud covered, C.
3. The intensity of the rain, I, which is influenced by the types of clouds present.

That is,

$$RR=f(S,C,I). \tag{1}$$

Once this basic relationship had been set down, the next decision required the identification of an area on a satellite photograph or nephanalysis most likely to affect the forecast station through the forecast period; namely, the next 24 hr. It seemed logical to assume that areas upwind of a station must be more important in such a context than those downwind or to either side. The extent of the critical area on any individual day would seem to be dependent partly on the variability of the wind, and partly on its strength. It was decided to investigate in each case *a quadrant of a circle* upwind from Valentia rather than the obvious alternative of a cloud transect. This would allow for some change in the bearing of approach of the advected weather during the forecast period and would relate the *radius of the quadrant* to an observed wind speed at a selected level in the troposphere.

In practice, the orientation of the cloud quadrant is determined (to the nearest 10°) by the near-noon radiosonde observation of the 800-mb wind. The radius is the 24-hr fetch of the wind, based on the noon 800-mb wind speed classed so that 0–4 kt is represented by 2 kt (Class 1), 5–9 kt by 7 kt (Class 2) and so on (figs. 1, 2). The 800-mb wind was chosen after initial tests since this level is generally near the base of the rain clouds over southwest Ireland, while being sufficiently high for the effects of frictional retardation and steering to be negligible. This choice of wind constitutes, perhaps, the most difficult decision taken in the design of the prediction model. Certainly, some of the inaccurate forecasts stemmed from this choice, especially when the prevalent weather systems were fast-moving. Under these conditions, the 800-mb wind direction and speed are liable to change rapidly. The use of forecast winds instead of observed winds at the beginning of the forecast period might eventually lead to better results. Such data were, however, unavailable to the author. Improvements might be achieved alternatively by compounding in some way the forecast paths of

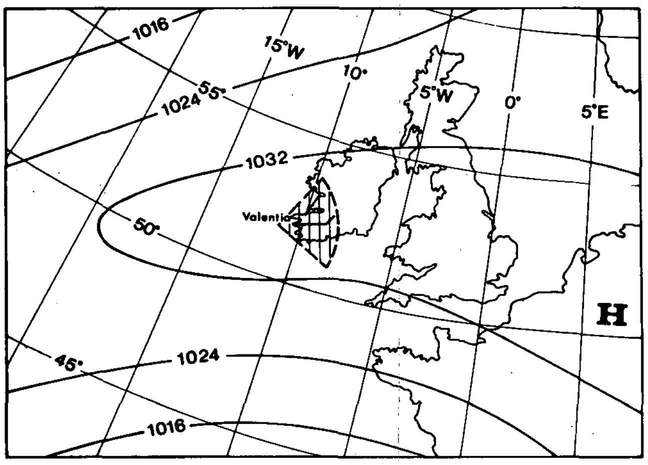

FIGURE 1.—Cloud quadrant for Valentia, Ireland, on Nov. 17, 1967, based on a 1200 LST 800-mb wind of 070° at 10 kt.

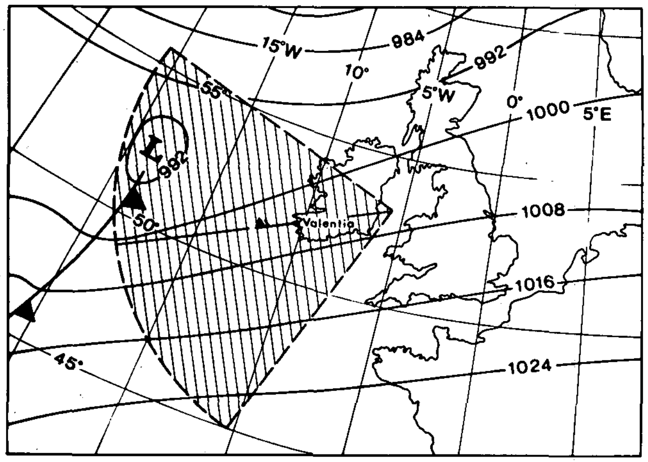

FIGURE 2.—Cloud quadrant for Valentia, Ireland, on Dec. 22, 1967, based on a 1200 LST 800-mb wind of 240° at 53 kt.

the approaching weather systems with the 800-mb winds or by varying the level of the wind observation employed in relation to the synoptic weather.

Despite the problems, however, the 800-mb choice led to encouraging results, which are detailed later. No allowances were thought necessary for the small errors stemming from the use of a standard set of right-angled quadrants constructed on tracing paper for overlaying on the U.S. Weather Bureau polar stereographic nephanalyses obtained on microfilm from the U.S. National Weather Records Center, Asheville, N.C. Nephanalyses were used in preference to photographs in an attempt to minimize personal subjectivity in the assessment of the likely rainfall performance of the satellite-viewed clouds. For operational purposes, it would seem desirable to compile more dependable and more detailed nephanalyses than those presently available, perhaps with two to three times their data content. These could be overlain by a Perspex circle,[1] graduated in 10° intervals around its circumference to orient a centrally attached, rotatable, quadrant marked concentrically in terms of the required range of quadrant sizes.

Summarizing these key points, we can express the rainfall forecasting model in the form

$$RR_K = S_W \bar{C}\left(\frac{I_1}{a} + \frac{I_2}{b} + \cdots + \frac{I_{10}}{j}\right) \tag{2}$$

where S_W is a rainfall probability, or synoptic weather index; $\bar{C}$ is a cloud cover index expressing mean cloudiness within a particular cloud quadrant; $I_1 \ldots I_{10}$ are cloud type or rainfall intensity indices specifying the types of clouds observed within that quadrant over proportions of its area of

$$\frac{1}{a} \cdots \frac{1}{j},$$

respectively, such that

$$\left(\frac{1}{a} + \frac{1}{b} + \cdots + \frac{1}{j} = 1\right).$$

RR_K is the resulting rainfall prediction index from which the rainfall forecast can be made. The equation is evaluated over an area of

$$\left(\frac{\pi r^2}{4}\right) \quad \text{n. mi.}^2,$$

where $r = 24VV$ and VV is the observed 800-mb wind speed in knots at or near the beginning of the forecast period. The cloud quadrant is oriented so that the 800-mb wind direction bisects it (figs. 1, 2).

Evaluating the Indices In the Rainfall Model

Before the rainfall prediction index could be calculated for any particular day, reasonable ranges of values had to be established for the three indices represented on the right side of eq (2). Since the rainfall estimation model is essentially a ranking procedure, simple ranking lists were compiled as appropriate in each of the three cases, ranging from 0 to 10. Low rainfall performances are at the lower end of the scale and high rainfall performances at the top.

Since the time available for research was restricted, the selected year of study (1967) was divided in half. January to June was used for the establishment of evaluated sets of indices, and July to December was used for testing and verifying the results in "forecasting" situations.

A synoptic weather index for Valentia. Rainfall occurrences for January through June 1967 were classified in terms of the single most important rain-producing weather organization affecting Valentia on the day of each occurrence. Each day was accorded a rain or no-rain status, the rain:no-rain scores for a number of easily identifiable weather organizations were summed, and the weather organizations were ranked accordingly. Table 1 summarizes the results. It shows, for example, that rain was recorded at Valentia 9 days out of 10 on the average when the passage of an occluded front or a frontal succession was indicated by the synoptic charts in the Daily Weather Report. At the other end of the scale, rain

[1] Mention of a commercial product does not constitute an endorsement.

TABLE 1.—*Rainfall probability index,* S_W, *based on the observed ratios of rain versus no-rain days associated with specific synoptic weather patterns*

Synoptic weather pattern	Rainfall probability (percent)	Synoptic weather (rainfall probability) index
Frontal succession Occluded front	90	9
Trailing cold sector	80	8
Warm front Warm sector Cold front	70	7
Nonfrontal trough Leading cold sector	60	6
Ridge of high pressure Cell of high pressure	30	3
Col	20	2

TABLE 2.—*Cloud cover indicated by nephanalysis cloud cover categories*

Nephanalysis cloud cover categories	Cloud cover (percent)
C+	100
C	90
MCO	65
MOP	35
O	10
CLEAR	0

was recorded on only 1 day in every 5 when col conditions were dominant. In the absence of longer term statistics in the literature, table 1 is a good approximation. The third column of table 1 lists the indices used in evaluating the rainfall probability index for any day during July through December 1967. For stations other than Valentia, specific tabulations of a similar kind should be compiled.

The cloud cover index. Table 2 lists cloud-cover categories commonly appearing on U.S. Weather Bureau nephanalyses in 1967. For each day's cloud quadrant, an appropriate estimate is made of mean cloud cover, using the values listed in table 2, along the lines laid down in eq (2). The initial cloud percentage estimate is rounded to the nearest 10 percent and divided by 10 to lie within a range from 0 to 10, commensurate with the other indices.

The rainfall intensity index. The basis for table 3 is the range of scales drawn up earlier for monthly rainfall estimation (Barrett 1970, 1971). Some alterations are necessary, however, to spread the range from 0 to 10, and to accommodate the wider range of cloud-type combinations occurring in middle latitudes compared with the Tropics.

Thus, the significance of the synoptic weather, the strength of cloud cover, and the nature of clouds in the advectional cloud quadrant are all ascribed similar ranges of significance. Together they are used to evaluate RR_K.

The rainfall prediction index. Rainfall prediction indices were evaluated for Valentia day by day for January through June 1967, using appropriate surface, upper air, and nephanalysis data. Unfortunately, the following

TABLE 3.—*Nephanalysis cloud categories and the cloud-type (rainfall intensity) index*

Nephanalysis cloud categories	Cloud type (rainfall intensity) index (I)	Index number
Cumulonimbus with cirrus	10	I_{10}
Cumulonimbus	9	I_9
Cumulonimbus with cumuliform	8	I_8
Cumulonimbus with stratiform	7	I_7
Layered stratiform, stratiform with cirrus, stratiform with cumuliform and cirrus	6	I_6
Stratiform, stratiform with cumuliform	5	I_5
Cumuliform with cirrus, scattered cumulonimbus	4	I_4
Cumuliform	3	I_3
Cirrus	2	I_2
Stratocumuliform	1	I_1
No cloud	0	0

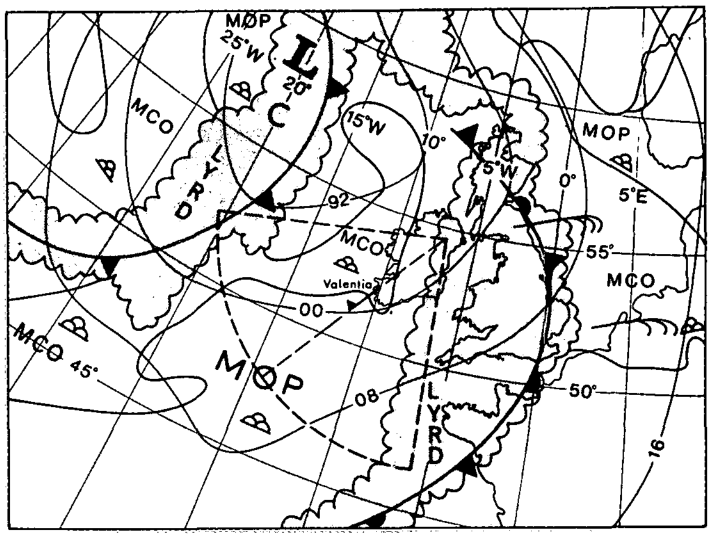

FIGURE 3.—Cloud quadrant for Valentia, Ireland, in July 1967 superimposed on nephanalysis to illustrate the rainfall prediction method. Synoptic weather index 6, cloud cover index 5 (i.e., 3/5 × 0.35 + 3/10 × 0.65 + 1/10 × 0.90), and cloud-type index 3 (i.e., 9/10 × 3 + 1/10 × 6). $RR_K = 90$.

departures from the ideal procedure were necessitated by the lack of synchronization in the observational data:

1. Daily rainfall figures were only readily available for the 24-hr periods from 0600 LST onward.
2. Radiosonde data are obtained at Valentia only from near-noon and near-midnight balloon flights. The midday observations were chosen for use in the present program.
3. In 1967, the time of ESSA satellite overflight and photography of Valentia was about 1400 LST.

Since the time differential between departures (1) and (3) is rather large (approximately 8 hr), we decided to compensate for this by investigating cloud quadrants specified by the noon radiosonde flights, but with their foci offset downwind by one-third of the appropriate radius. Thus, the focus of the quadrant in figure 1, like that in figure 2, represents 0600 LST on day 1. In either

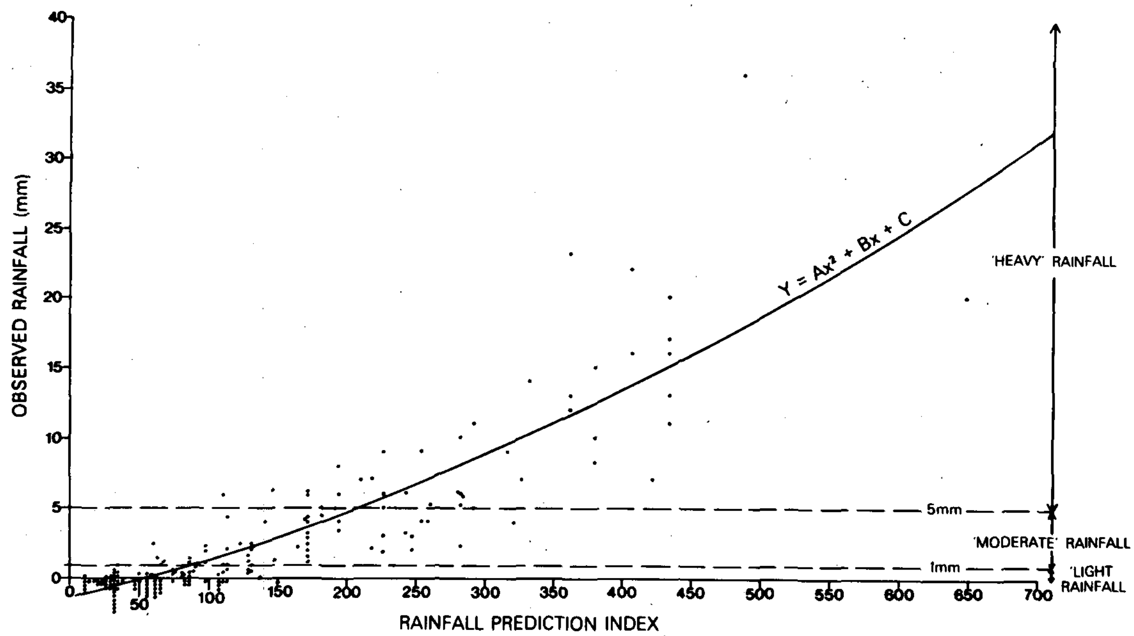

FIGURE 4.—Scatter diagram for Valentia for January through June 1967 portraying plots of evaluated rainfall prediction indices (RR_K) versus rainfall measurements.

TABLE 4.—*Valentia daily rainfall totals for January through June 1967 grouped to give approximately equal populations in the three classes, heavy, moderate, and light rainfall*

Class	Lower limit	Upper limit	Number of days in class
	(mm)	(mm)	
Heavy	5. 1	No limit	40
Moderate	1. 1	5. 0	41
Light (or little)	0. 1	1. 0	38
None	–	–	62

case, the situation of Valentia represents 1400 LST, and the intersection of the circumference of the quadrant with its bisector represents clouds expected to lie over Valentia at 0600 LST on day 2, assuming that the 800-mb wind does not change in force or direction. Operationally, it would be highly desirable to synchronize rainfall, satellite, and radiosonde data.

In view of these problems within the test case, daily rainfall is forecast retrospectively for 8 hr and forward for 16 in comparison with the time of satellite photography. Since it is the general level of performance of the model that is in question, such a course was not unreasonable under the circumstances. Plots of rainfall prediction indices for offset quadrants versus observed 24-hr rainfall from 0600 LST seem likely to be fairly reliable indicators of the results we might anticipate under ideal conditions. Figure 3 illustrates the method of rainfall prediction index evaluation for one selected day. Complete results for each day from Jan. 1 to June 30, 1967, are portrayed in figure 4.

The best-fit regression is specified by the equation

$$y=0.000032x^2+0.024075x-1.299839. \tag{3}$$

This quadratic polynomial had coefficients significant at the 5-percent and 1-percent levels. It served to facilitate the choice of the rainfall prediction index classes used later in the verification exercise. Observational data from Valentia for January through June 1967 were analyzed to define appropriate local boundaries for the three categories of light, moderate, and heavy rainfall. A fourth class; namely, "no rainfall," was recognized also. Table 4 shows that approximately one-third of all days were found to be dry when rainfall "traces" ($<$0.1mm) were discounted. Almost exactly equal numbers of days fell into classes bounded by 1.0 mm and 5.0 mm. These values were, therefore, adopted as the necessary class limits for forecasting purposes.

It is clear that where the regression line in figure 4 crosses the various class limits it is not possible to forecast with confidence a single class of rainfall from appropriate values of x. Consequently, we decided to use an expedient already common in other weather forecasting procedures to acknowledge and allow for such uncertainties. Three intermediate rainfall classes were nominated, each one overlapping pairs of neighboring classes within the basic range of four. For example, an additional class was established astride the intersection of the regression line and $y=5.0$; namely, "moderate or heavy" rainfall. The limits of the four basic and three "either/or" classes were selected from the evidence in figure 4 so as to give the best possible ratios of rightly: wrongly classified points in each column. Table 5 details the limits of each forecast category chosen in this way. Figure 5 displays the relationships between rainfall prediction indices, rainfall prediction classes, and the class limits of light, moderate, and heavy rain in diagrammatic form. Rainfall prediction indices were calculated for each day from July through December 1967, and the results translated into forecast classes through table 5 or figure 5.

499-057 O - 73 - 5

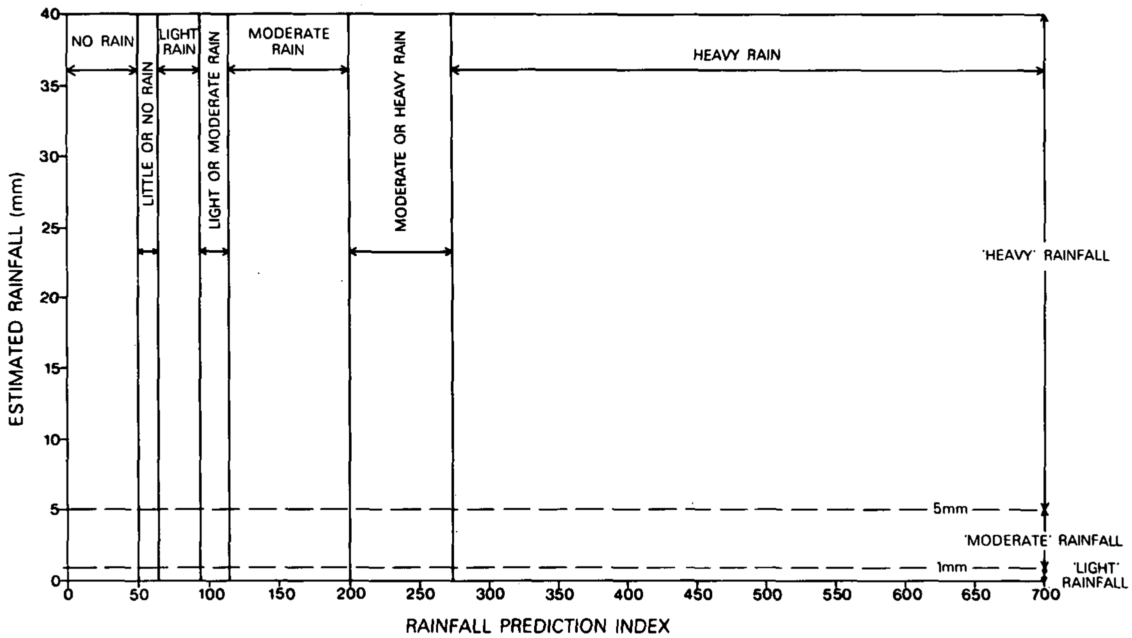

FIGURE 5.—Relationships between rainfall prediction indices, rainfall prediction classes, and appropriate rainfall class units for Valentia.

TABLE 5.—*Daily rainfall classes, specified in terms of rainfall coefficients for Valentia, January through June 1967*

Class	Lower limit (rainfall pred. index)	Upper limit (rainfall pred. index)
		(theoretical max.)
Heavy	276	900
Moderate or heavy	199	275
Moderate	116	200
Light (lt) or moderate	96	115
Light	66	95
Little or none	51	65
None	0	50

3. VERIFICATION OF RESULTS

"Operational" results of the daily application of the method were tabulated for comparison with observed rainfall totals. Table 6 is a complete statement for July 1967, listing all the variables involved in the forecasting method. For example, on July 1 (day 1) a nephanalysis cloud quadrant of class 5 (radius=22 n.mi./hr × 24 hr) was positioned at Valentia with an orientation of 250°. Within that quadrant, cloud cover was approximately six-tenths, and the cloud type (rainfall intensity) index was evaluated at 2. An approaching occluded front warranted a rainfall probability index of 9. Consequently, the rainfall prediction index for the forecast period was (9×6×2)=108. Table 5 (or fig. 5) associates this with light or moderate rainfall. Table 6 (column 10) indicates that the observed rainfall from 0600 LST on July 1 to 0600 LST on July 2 was 0.7 mm. Within the limits laid down earlier, the forecast was therefore correct.

Table 7 gives generalized scores for the results obtained month by month through the trial period. The ratio of right:wrong forecasts is almost 3:1, since 74.3 percent of the forecasts suggested the right rainfall classes or choice of adjacent classes. With improvements, it might be possible to eliminate the either/or categories. At present, their removal would lower the accuracy of the forecasts to a little over 50 percent, a much less acceptable evel, but one that is still much better than chance.

Finally, table 8 compares the daily forecasts with the rainfall measurements in terms of their respective classes. Apart from the happy preponderance of correct forecasts, it is encouraging to note that less than 5 percent of all forecasts were so incorrect as to be two rainfall classes removed from reality.

4. CONCLUSIONS AND RECOMMENDATIONS

It seems fair to claim that there is value in a scheme like the one outlined in this paper, even though its empirical nature may seem out of harmony with many modern forecasting procedures, impressive as they are in physical and mathematical terms. Rainfall forecasting is still largely dependent on the skill of the forecaster and may be of critical importance in regions liable to human and/or economic disaster through flooding. This satellite-based method seems capable of providing detailed and reasonably accurate results even in its present form. It is sufficiently flexible to be applied in many widely separated areas dominated by weather advected from regions of limited conventional data such as the coast of western Europe, western Canada and southern Alaska, southern South Africa, southern Chile, southwestern Australia, and New Zealand. Tropical regions seem likely to pose different kinds of problems, although even there the

TABLE 6.—*Formulation and verification of forecasts for Valentia, July 1967*

24 hr commencing 0600 LST on July	800-mb wind speed near local noon	Quadrant number	800-mb wind direction near local noon	Rainfall probability index	Cloud cover	Cloud-type (rainfall intensity) index	Rainfall prediction index	Rainfall prediction	24-hr observed rainfall from 0600 LST	Accuracy of forecast
	(kt)		(°)		(tenths)				(mm)	
1	21	5	250	9	6	2	108	lt/mod	0.7	right
2	23	5	260	6	5	3	90	lt	1.0	right
3	30	7	270	3	7	3	63	lt/none	0.6	right
4	13	3	340	3	8	4	96	lt/mod	0.0	wrong
5	9	2	180	3	9	1	27	none	0.0	right
6	23	5	230	7	7	6	294	heavy	15.0	right
7	17	4	300	8	9	4	288	heavy	7.0	right
8	36	8	300	3	6	3	54	lt/none	0.1	right
9	21	5	260	3	4	3	36	none	0.0	right
10	16	4	250	3	7	3	63	lt/none	0.0	right
11	8	2	230	3	4	3	36	none	0.0	right
12	13	3	160	6	2	3	36	none	0.0	right
13	11	3	180	3	7	9	189	mod	2.0	right
14	13	3	260	7	6	3	126	mod	1.3	right
15	21	5	210	7	9	6	378	heavy	25.0	right
16	46	10	210	8	7	5	280	heavy	2.1	wrong
17	30	7	200	8	8	2	128	mod	0.4	wrong
18	20	5	220	6	5	3	90	lt	0.3	right
19	14	3	250	8	6	2	96	lt	0.5	right
20	16	4	260	2	7	1	14	none	0.1	wrong
21	7	2	180	2	10	9	180	mod	4.0	right
22	4	1	130	8	4	3	96	lt/mod	1.0	right
23	17	4	240	6	5	4	120	mod	0.5	wrong
24	30	7	270	9	8	5	360	heavy	8.0	right
25	26	6	250	3	7	5	105	lt/mod	1.0	right
26	28	6	250	3	10	5	150	mod	1.1	right
27	25	6	260	3	8	3	72	lt	1.0	right
28	19	4	280	6	8	5	240	mod/heavy	9.0	right
29	23	5	240	7	9	4	252	mod/heavy	2.3	right
30	31	7	230	8	8	3	192	mod	0.3	wrong
31	21	5	230	2	7	5	70	lt	0.0	wrong

TABLE 7.—*Comparison of daily rainfall forecasts and observations for Valentia, July through December 1967, in terms of the accuracies of the forecast classes*

Month	Right forecasts	Wrong forecasts	No comparison possible
July	24	7	–
August	24	6	1
September	23	7	–
October	22	9	–
November	20	10	–
December	23	8	–
Totals	136	47	1

TABLE 8.—*Verification of daily rainfall forecasts (plotted versus observations) for Valentia, July through December 1967. (Correct forecasts are underlined). One day (in August) could not be classified.*

Observed rainfall	Estimated rainfall							Totals
	None	Little or none	Light	Light or moderate	Moderate	Moderate or heavy	Heavy	
Heavy	1		1		5	8	34	49
Moderate	3	1	8	7	31	7	3	60
Light	7	4	10	7	6	2	2	38
None	22	5	5	3	1			36
Totals	33	10	24	17	43	17	39	183

method might prove useful, especially in regions like the Caribbean and parts of southeast Asia, that are influenced strongly by mobile weather systems from the east. Certainly, the basic method is capable of much further development and refinement. Ongoing work at the University of Bristol indicates that worthwhile forecasts may be possible through the operation of similar, though not identical, models even in such a synoptically complex situation as the Indian summer monsoon (Hamilton 1973).

The chief recommendations that may be made for further work include the following:

1. Conduct comparative studies for Valentia to assess the best possible performance of the basic model (e.g., using different methods of cloud quadrant identification).

2. Since the standard U.S. National Weather Service nephanalyses are often a source of error because of insufficient detail of local variations in cloudiness, benefits accruing from the use of more detailed cloud charts should be investigated.

3. As far as possible, daily rainfall totals should be employed for the 24-hr periods commencing with the local time of satellite

photography or radiosonde flights, these two usually being osecl together. This would remove the necessity for offsetting the foci of the cloud quadrants downwind from the forecast station. For each new station, appropriate values must be established for the delimitation of the rainfall forecast classes.

4. Since very heavy falls of rain are of special significance to the hydrologist and flood forecaster, the possibility of forecasting "very heavy" rainfall as an additional category should be examined.

5. Ascertain whether daily rainfall forecasting could be based on high-resolution infrared data instead of satellite photographs or nephanalyses.

6. Determine whether a method of this kind could be conducted all or partly by automatic means (e.g., through the use of densitometry techniques for evaluations of cloud cover and dominant cloud types).

ACKNOWLEDGMENTS

The author thanks W. A. Follansbee, Applications Group, NESS, Suitland, Md., for details of the modifications made to his monthly rainfall estimation model to permit its application to daily rainfall events.

REFERENCES

Barrett, Eric C., "The Estimation of Monthly Rainfall From Satellite Data," *Monthly Weather Review*, Vol. 98, No. 4, Apr. **1970**, pp. 322–327.

Barrett, Eric C., "The Tropical Far East; ESSA Satellite Evaluations of High Season Climatic Patterns," *Geographical Journal*, Vol. 137, No. 4, London, England, Dec. **1971**, pp. 535–555.

Clapp, Philip F., and Posey, Julian, "Estimating Environmental Parameters From Macro-scale Video Brightness Data of ESSA Satellites," Mimeographed paper, Extended Forecast Division, NMC, Suitland, Md., Jan. **1970**, 27 pp.

Committee On Space Research (COSPAR), "Status Report on the Application of Space Technology to the World Weather Watch," COSPAR Working Group, London, June **1967**, 144 pp.

Dennis, A.S., "Rainfall Determination by Meteorological Satellite Radar," *Final Report*, SRI 4080, Stanford Research Institute, Menlo Park, Calif., Apr. **1963**, 105 pp.

Follansbee, W. A., "Estimation of Average Daily Rainfall From Satellite Cloud Photographs," unpublished manuscript, Applications Group, National Environmental Satellite Service, Suitland, Md., Aug. **1972**, 18 pp.

Follansbee, Walton A., "Estimation of Average Daily Rainfall from Satellite Cloud Photographs," NOAA *Technical Memorandum*, NESS 44, National Environmental Satellite Service, Suitland, Md., Jan. **1973**, 39 pp.

Hamilton, M. G., "Satellite Studies of the South Asian Summer Monsoon," Ph. D. Thesis, University of Bristol, England, **1973** (in preparation).

Hope, John R., "Path of Heavy Rainfall Photographed From Space," Bulletin of the *American Meteorological Society*, Vol. 47, No. 5, May **1966**, pp. 371–373.

Johnson, D. H., Dent, D. W., and Preedy, B. H., unpublished notes reported in D. H. Johnson, "The Role of the Tropics in the Global Circulation," *Proceedings of the R.M.S./A.M.S. Joint Conference on the Global Circulation of the Atmosphere, August 25–29, 1969, London, England*, Royal Meteorological Society, London, **1969**, 257 pp. (See pp. 113–136).

Lethbridge, Mae, "Precipitation Probability and Satellite Radiation Data," *Monthly Weather Review*, Vol. 95, No. 7, July **1967**, pp. 487–490.

Thaddeus, P., "A Micro-wave Radiometer for the Nimbus-D Meteorological Satellite," proposal made to Goddard Space Flight Center, Goddard Institute for Space Studies, New York, N.Y., Aug. **1966**, 22 pp.

World Meteorological Organization, "The Role of Meteorological Satellites in the World Weather Watch," *World Weather Watch Planning Report* No. 18, Geneva, Switzerland, **1967**, 38 pp.

[*Received August 10, 1972; revised September 5, 1972*]